Modeling mountain building, numerical trade off between erosion law and crustal rheology

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Abstract. Coupling between erosion and tectonics are thought to play a determinant role in mountains evolution. Here, we investigate the interplay in this coupling between the assumed erosion law and the crustal rheology at the margin of a collisional plateau, like the Himalaya of central Nepal. Lithospheric deformation is calculated over a time scale of 100 kyr by a two-dimensional finite elements model that incorporates the rheological layering of the crust and the main features of the convergence across the range including shortening rate and geometry of the Main Himalayan Thrust fault. For the upper boundary condition, several surface processes were tested: a linear diffusion model and a 1D1/2 integrative model including fluvial incision along the fluvial network and hillslope erosion by landsliding. Model results and their sensitivity to the chosen combinations of erosion law and crustal properties are discussed in light of the constraining geologic and geomorphologic observations (topography, river elevation, denudation and fluvial incision rates). In contrast with the conclusions of Cattin and Avouac [2000] where a compliant, quartz-rich crustal rheology and diffusion law were required, we rather propose to use a composite quartz-diabase rheology for the crust associated with fluvial incision to account for erosion and elevation profiles across the Himalaya of central Nepal. More generally, it is proposed that, because of the interplay between the dominant denudation conditions and rheology of the crust, well documented erosion rates and processes

can provide significant constrains on crustal properties within an active orogen.

1. Introduction

The land surface is a dynamic interface that results from the combination of tectonic uplift and denudation. Knowledge of the linkages and feedbacks between those two processes is essential for the understanding of the structure and the evolution of mountain belts. Because of several numerical limitations, few 3D studies with full coupling between tectonics and erosion have been conducted so far. Most of the thermomechanical finite element models are bidimensional, where erosion processes are usually reduced to a 1D process acting on the surface profile. Erosion is either resumed to a diffusion law [Avouac and Burov, 1996; Cattin and Avouac, 2000], or to a linear relation of the surface slope [Beaumont et al., 2001], or to a simple river incision law where the mean topographic profile is represented by a river profile [Willet, 1999]. These simplified models ignore the respective role of river network and hillslopes in controling the morphology and evolution of the landscape. In this paper we investigate the influence of the assumed erosion law and of the rheological properties of the crust on crustal deformation through the use of a 2-D thermo-mechanical finite element model. We apply our approach to the Himalaya of central Nepal, one of the best documented example of active mountain belt. After a short presentation of the main features of the Himalayan orogenic belt, we describe the modeling approach and the two distinct erosion laws we want to test. We next compare the existing geomorphologic observations (including horizontal shortening, topography, river elevation, denudation and fluvial incision rates) with model-simulated landscape produced by various combinations of erosion law and crustal properties. We finally discuss the sensitivity of our results and try to highlight the most discriminant observations to unravel rheologic and erosional conditions prevailing in a mountain range.

2. Geodynamical Setting and characteristics of the fluvial network

The Himalayan belt has resulted from the ongoing collision between the Indian and Asian plates. It is one of the most active orogen of the Earth, characterized by a steep topographic front from the 5000m elevated Tibetan Plateau down to the Gangetic plain. This topographic step goes through four major morphotectonic domains: the rugged South Tibetan plateau, the High Himalaya (HH) with deep gorges and $\sim$ 8000m summits, the lower relief of the Lesser Himalaya (LH), and the frontal low elevation relief of the Siwaliks Hills. The Himalayan range is affected by an intense ongoing seismicity [e.g. Ni and Barazangi, 1984; Pandey et al. 1995], and displays abundant records of active deformation [Nakata, 1972]. The long term shortening rate across the range is $\sim$ 20 mm.yr^{-1} [Lyon Caen and Molnar, 1985; Armijo et al., 1986]. During the Holocene, this convergence has been mostly transferred to the southernmost thrust or Main Frontal Thrust (MFT) [Lavé and Avouac, 2000]. This frontal fault branches on the Main Himalayan Thrust (MHT) rooting at 30-40km deep beneath the South Tibet [Zhao et al., 1993], and displaying a ramp and flat geometry beneath the HH and LH domains [Schelling and Arita, 1991; Lavé and Avouac, 2001]. Several major north south rivers drain the Himalayas of Nepal from the southern Tibet down to the Indo-Gangetic plain. In Central and East Nepal, across the HH, those trans-himalayan rivers are distant of 50km on average before joining, in the southern part of the LH, two major rivers systems, the Narayani and Sapt Kosi basins. Both rivers are tributary of the Ganga. Precipitations in Nepal are controlled by the barrier of the Himalayas, with a brutal condensation against the HH of the wet air coming from the Indian ocean during monsoon. Whereas a marked rain shadow develops on the north flank of the HH, the prominent fluvial network of the south flank, fed by intense rainfalls is deeply entrenched in the topography and actively participate to the denudation of the orogen (figure 1). Transhimalayan rivers and fluvial terraces profiles [Lavé and Avouac, 2000, 2001] or thermochronologic data [Burbank et al., 2003] suggest in addition that erosion is maximal across the Siwaliks and the HH, lower in the LH and minimal in South Tibet.

3. Modeling approach

Following Cattin and Avouac [2000], our model is based on a 700 km long N18 cross section perpendicular to the range, from the Gangetic Plain to the Tibetan Plateau (see figure 1 for the location). We use a 2-D finite element model, ADELI [Hassani et al., 1997] that accounts for the mechanical layering of the crust, the non-newtonian rheology of rocks, and their dependencies on temperature and pressure. Three lithological layers are distinguished: the upper and lower crusts, and the upper mantle. Each layer has specific mechanical properties. We use the empirical rheological equations and laboratory-derived material properties for quartz, diabase and dry olivine (see supplemented electronic document 1). Those rheologies are dependent on temperature which is prescribed as an initial condition [Henry et al, 1997] and do not evolve during the simulation, considering the typical duration of ∼100 kyr (see Appendix 1 (suppl. Electr. Material) for the detail of time scenario). For the different runs, this duration was usually sufficient to reach a stabilized topographic profile, i.e. an average equilibrium between uplift and erosion (in a Lagrangian sense). The principal geometric characteristics of our model are similar to Cattin and Avouac's model [2000] (figure 2). The geometry of the Moho beneath South Tibet is derived from INDEPTH seismic profile [Zhao et al., 1993] and from gravity data [Cattin et al., 2001]. The boundary conditions applied to the system are constrained by geodynamics data: we apply a 20 $mm.yr^{-1}$ horizontal velocity on the northern vertical face for depth above 40 km and leave vertical velocities free for the other vertical faces. The structure is supported by hydrostatic pressure at its base which allows isostatic compensation and thus realize a coupling between uplift and denudation. Due to the duration of our simulations we are not taking into account the seismic cycle and the slip on a low friction MHT is considered as continuous. Our main goal is to test the importance of the upper boundary condition imposed with the introduction of surface processes on the evolution of the system.

4. Surface processes

We distinguish two domains in term of surface processes: the foreland, south of the MFT ($x<0$), with active sedimentation and the mountain range north of the MFT, dominated by active erosional processes. The first domain, the Indo-gangetic basin is classically described as a low elevation over-filled basin [Lyon-Caen and Molnar, 1985]: we thus assume in the following a constant $\sim$ 0m elevation for it. In the range, two distinct erosion models are explored: a diffusion model and a detachment limited fluvial incision model including an implicit description of the tributaries and hillslope in the mean topography (Lavé, in prep.). The diffusion model is probably one of the most simple self-consistent model, in the sense that erosion, transport and deposition are described by a single relation. The basic form of this relation is a 1-D linear diffusion law that simply writes :

$$\left(\frac{\partial \bar{h}}{\partial t}\right)_x = \kappa \left(\frac{\partial^2 \bar{h}}{\partial x^2}\right)_x , \tag{1}$$

where κ is the mass diffusivity coefficient, $\bar{h}$ is the elevation of the topography and x is the distance from the MFT. The diffusion model can be applied to describe the shape and evolution of small scale topographic feature. However, it hardly applies at the scale of a whole mountain range, because it can not account for the advective nature of the fluvial processes. Recent studies have, in particular, underlined the key role played by the fluvial incision in leading unglaciated landscape denudation [e.g. Whipple and Tucker, 1999]. Whereas different functional forms have been proposed to model fluvial incision [eg. Whipple and Tucker, 2002], in an attempt to develop a simple approach, we have used a detachment limited relation that provides satisfying first order results in the Subhimalaya [Lavé and Avouac, 2001]. This relation states that bedrock incision rate of a river is proportional to the fluvial shear stress τ in excess of some threshold τ_c, computed from the river slope S_x and flood discharge derived from rainfall profile (figure 2) [Lavé and Avouac, 2001]:

$$\left(\frac{\partial h_{riv}}{\partial t}\right)_x = K_x(\tau - \tau_c) \tag{2}$$

with,

$$\tau = k_1(\bar{P}_x - P_r)^\gamma (L(X-x))^\beta \left(\frac{S_x}{s_0}\right)^\alpha , \tag{3}$$

where K_x is the erodability coefficient (figure 2) depending on rock strength, k_1 a coefficient that depends on the river network geometry, sediment size and flood distribution, L the width of the watershed, s_0 the sinuosity of the river and α, β, γ are exponents considered as constant in our study area. $\bar{P}$ is the average precipitation on the watershed and P_r some treshold runoff. X is the abscissa of the drainage divide. Despite their leading role, the main rivers do not account for the mean topography, which represent the pertinent variable for the upper boundary condition of mechanical modelling. The elevation profile of the transhimalayan river represents in fact the base level for the network of tributaries which are draining the whole topography, from their sources at the base of the hillslopes to their confluence with the trunk stream. At a given abscissa, the mean elevation of the topography $\bar{h}$ is therefore the sum of three contributions: (1) the elevation of the main river h_{riv}, (2) the fluvial relief associated to the tributaries Δh_{trib} that we assume to be controlled by the same incision law as the main river and (3) the relief of the hillslope from the fluvial network to the crest Δh_{hill}. In active orogens, hillslopes are dominated by landslides [Hovius et al., 1997]: we thus assume that they display a critical slope angle of repose θ_c and that they react instantaneously to any local base level drop. A new formalism to integrate the fluvial relief associated to the tributaries network is proposed by Lavé [in prep.] and enable to compute at each time step the changes of the elevation of the trunk stream from equation 2 and of the changes in mean topography according to

$$\left(\frac{\partial \bar{h}}{\partial t}\right)_x = \left(\frac{\partial h_{riv}}{\partial t}\right)_x + K_x(k_2(P_x - P_r)^\gamma \Delta h^\alpha_{trib_x} - \tau_c) \quad (4)$$

with,

$$\Delta h_{trib} = \Delta h_{total} - \Delta h_{hill} = \Delta h_{total} - \frac{\Delta l}{2} \tan \theta_c, \quad (5)$$

where k_2 is a coefficient which depends like k_1 on the tributary network and the flood distribution, and Δl the horizontal distance between the crest and the base of the hillslope. The different parameters of the two erosion models are detailed in Appendix 2 (supplemented electronic material).

5. Sensitivity to the erosion law

To investigate the influence of the denudation law, the rheological layering used is quartz (upper crust), diabase (lower crust) and wet olivine (mantle) as on figure 2. The comparison between the two tested erosion models is carried out on 4 different profiles: mean elevation, horizontal velocity, uplift and erosion rates (figure 3). The river elevation and incision rates are specific to the fluvial incision model, and thus do not appear in the diffusive case. The two models display very similar profiles of horizontal velocity: the southward transfer of the Himalayan shortening is allowed by the low friction condition on the MHT [Cattin and Avouac, 2000]. In contrast, the uplift and erosion rates display distinct profiles suggesting that part of the vertical motion is controlled by deformation in the middle and lower crust in response to erosional unloading. Diffusion processes localize the highest erosion at the southern edge of Tibetan plateau (x$\sim$ 140 km on our profile), associated with the maximum amount of slope variations along the profile. With the fluvial incision model, the erosion of the whole topography acts at a slower rate than incision of the main river: less denudation leads to a faster southward migration or gravitational spreading of the plateau and counteracts against river regressive erosion. Finally, diffusion based landscape evolution leads to relatively smooth topographic profiles, with continuous slopes variations. By contrast using the incision law allows to preserve a clear slope transition between the LH and HH. This enhances that, in addition of being the most realistic of the two erosion laws, only the fluvial incision model provides a good agreement with all the available observations: i.e. the highest rates of erosion and incision across the HH (x$\sim$ 100 km in Figure 3) [Lavé and Avouac, 2001; Burbank et al., 2003], positive denudation in the LH, $\leq$ 1 mm.yr^{-1} of sedimentation in front of the MFT [Lavé and Avouac, 2000], the sharp topographic transition between the LH and HH.

6. Sensitivity to the crustal rheology

In contrast with our results, Cattin and Avouac [2000] obtained with a linear diffusion model a good fit to the geophysical observations data including the estimated pattern of river incision. However Cattin and Avouac [2000] have been using a homogeneous quartz-like rheology for the crust. We thus suspect a trade off between the assumed denudation condition and the rheological properties of the crust. To test this hypothesis we calculate the deformation field resulting from various combinations of erosion law (diffusion or fluvial incision) and crustal properties (homogeneous or composite). As shown in figure 4, a complex interplay indeed exists between surface processes and crustal properties. A soft rheology for the lower crust (quartz) induces a gravitational collapse of the plateau. This localizes the maximum slope variations at the foothill of the HH, leading to a maximum of erosion by diffusion across the HH. In contrast, with the fluvial incision model, this collapse increases the river embanking, the denudation and uplift rates within the LH, which is found inconsistent with available data in LH [Lavé and Avouac, 2001]. The other end member diabase like crustal rheology implies a stronger coupling between mantle and crustal deformation. This model predicts a buckling of the lithosphere. Using diffusion law with this rheology gives sedimentation in the Lesser Himalaya, and a denudation peak far too the North. Fluvial incision, associated to this unrealistic diabase like upper crust, displays also the same inconsistent peak of erosion in South Tibet and provides a poorer fit of the erosion profile than when using a composite rheology.

7. Conclusion

Among the reduced set of simulations presented in this paper, two combinations provide a good fit to denudation data: (1) the Cattin and Avouac's model in which an homogenous quartz like rheology is associated with diffusion, and (2) our model with composite crustal rheology (quartz-diabase) associated with fluvial incision including erosion of the whole topography. However, the first combination can not provide a good fit to the whole set of observations: only a fluvial incision based model preserves a clear slope transition between the LH and HH, and only a strong lower crust can account for ≤ 1 mm/yr of sedimentation in the Gangetic plain. A diabase-like rheology for the lower crust, which minimize the decoupling effect between crust and mantle, is in addition required to produce the strength of the Indian lithosphere as inferred from gravity anomalies measurements [Cattin et al., 2001]. Our exploration of the different model parameters (i.e. the mechanical properties of the crust, the MHT geometry and the apparent friction on it, or the denudation law) is far to be exhaustive. However, these preliminary results highlight several concerns when studying active orogens. First, the hypothesis of the dominant erosion law may have major consequences in terms of denudation and uplift pattern. Second, because of the trade off between the denudation pattern and the crustal rheology, the use of a realistic denudation law, calibrated with field measurements, allows to put significant constraints on the properties of the crust. Finally, it has to be noted that for a given range several sets of different observation are necessary to fully decipher the different combinations of rheologic, tectonic and erosion models. In our case study focused on the Himalayas of central Nepal, the incision and denudation rates, the sedimentation rate in the foreland basin, the topographic profile appears as the respective most constraining data.

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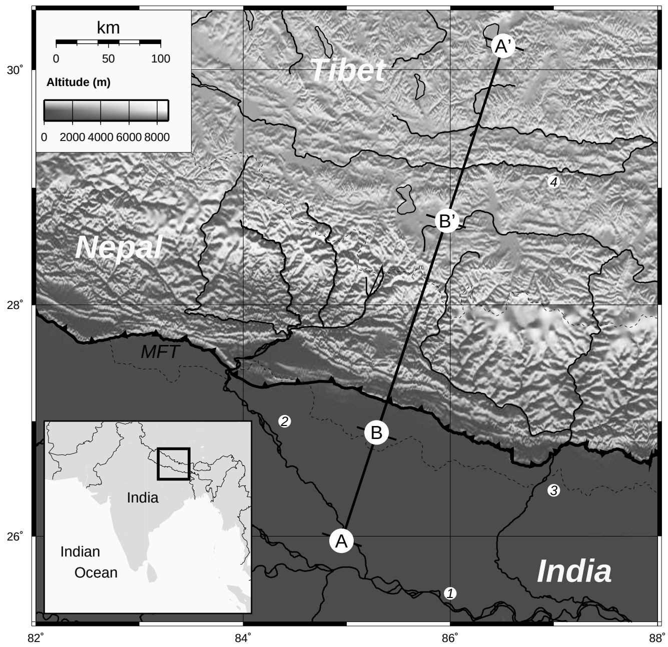

Figure 1. Topographic map of the studied area (GTOPO30 digital elevation model), showing the principal hydrographic features, the position of the Main Frontal Thrust, and the cross sections AA' (figure 2) used in the modeling and BB' presented on figures 3 and 4. 1-Ganga, 2-Narayani, 3-Sapt Kosi, 4-Tsangpo.

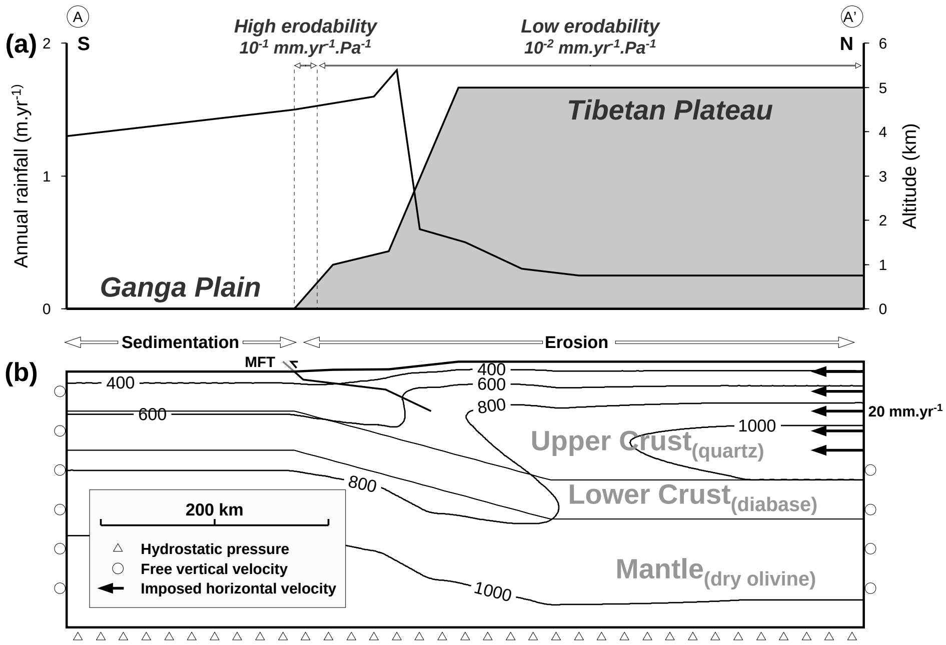

Figure 2. Main features of the model.(a) Rainfall profile (black line) and initial topography (gray area) used in this study. Dashed line gives the location of the high erodability area associated with the Siwaliks foothills. (b) Geometry of the system, temperature field (K), rheological units, and boundary conditions used for the mechanical modeling. The model is loaded with gravitational body forces. A fault with a simple Coulomb friction law is introduced and follows the ramp and flat geometry proposed for the MHT. In the foreland south of the MFT (x<0), erosion balances tectonic uplift or subsidence. In the range (i.e. north of the MFT) landscape evolution is controlled by the erosion law (diffusion law or river incision law).

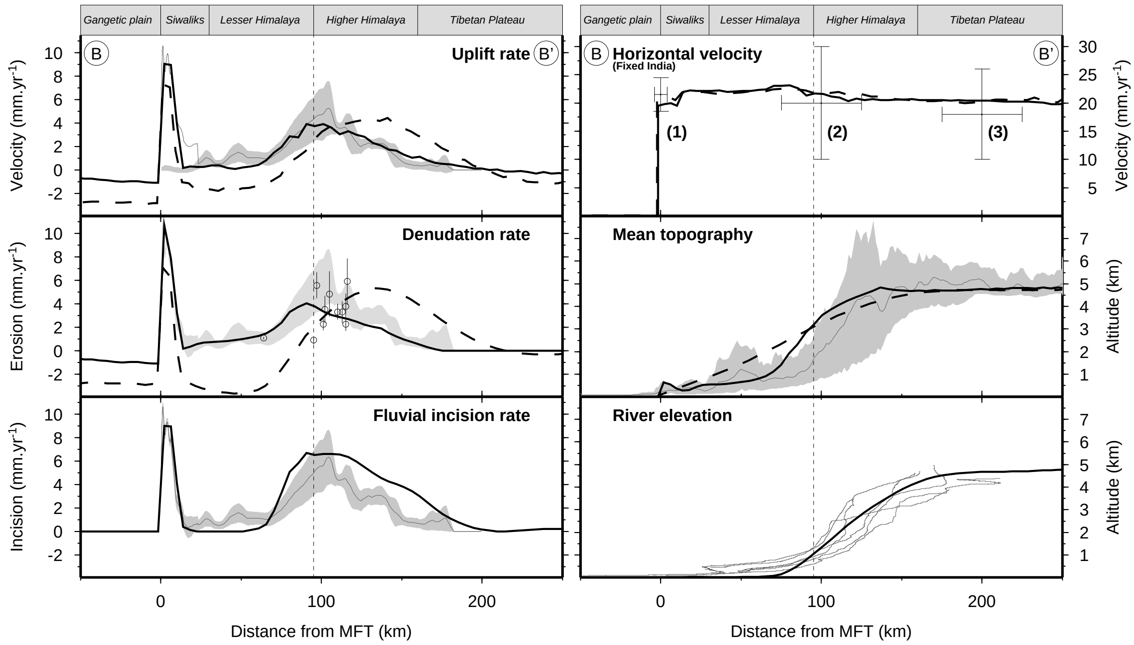

Figure 3. Fluvial incision model (black line) and diffusive model (dashed line). Uplift, denudation and incision profiles are confronted to profiles across the range from Lavé and Avouac [2001], and to fission track datas from Burbank et al. [2003] for the denudation profile (denudation rates obtained using the thermal model from Henry et al. [1997]). The control points on horizontal velocity are derived from folding of fluvial terraces in the Siwaliks (1) [Lavé and Avouac, 2000], progradation of the sediments in the Gangetic Plain and flexure of the indian plate (2) [Lyon-Caen and Molnar, 1985] and quaternary grabbens extension in Southern Tibet (3) [Armijo et al., 1986]. Topography is derived from GTOPO30 DEM, and river elevation from Lavé and Avouac [2001].

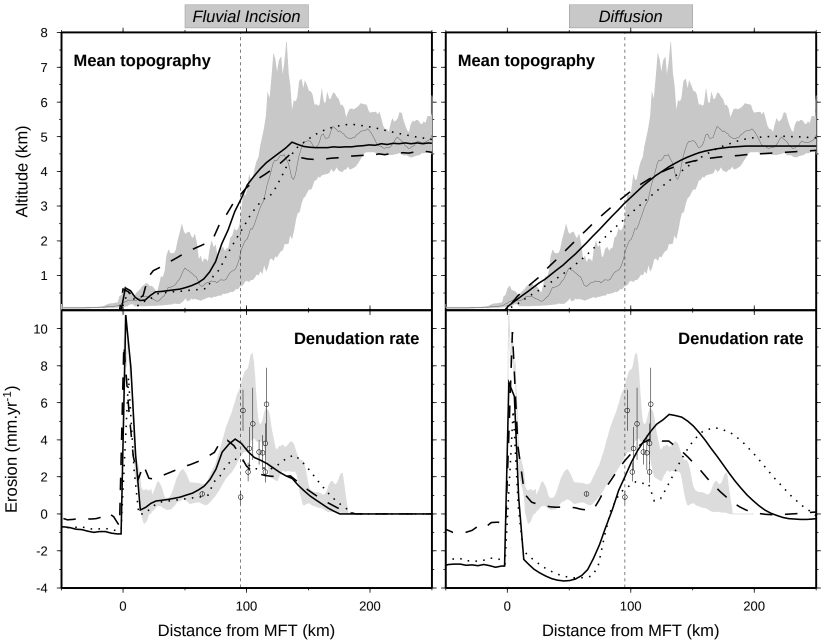

Figure 4. Effect of the assumed erosion law (fluvial incison and diffusion) on the rheology of the crust to fit topography and denudation profiles. Black line: quartz (upper crust), diabase (lower crust). Dashed line: quartz (upper and lower crust). Dotted line: diabase (upper and lower crust)